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(54) [Title of the Invention] METHOD FOR ANNEALING SOLID SAMPLE AND METHOD FOR FORMING SEMICONDUCTOR IMPURITY-DOPED LAYER

(57) [Abstract]

[Object] The conventional annealing technique is effective for activation of an

impurity-doped layer. However, there has been a problem in that the entire substrate is heated to a high temperature of about 1000 °C and an injected impurity is diffused to a deep part of the substrate even by a short-time-heating of about 10 seconds.

[Solution] A solid sample is irradiated with an electromagnetic wave, and lattice vibration (phonon) is directly excited, whereby vibration, rearrangement, and diffusion of atoms, molecules, and lattice defects are performed in a thermally non-equilibrium state.

[Scope of Claims]

[Claim 1] A method for annealing a solid sample characterized by comprising the steps of:

performing vibration, rearrangement, and diffusion of an atom, a molecule, and a lattice defect in a thermally non-equilibrium state by irradiating a solid sample with an electromagnetic wave to directly excite lattice vibration (phonon).

[Claim 2] A method for forming a semiconductor impurity-doped layer in formation of a semiconductor over a silicon wafer, characterized by comprising the steps of:

performing activation of an impurity element in a thermal non-equilibrium state to perform low temperature activation of an ultrashallow junction layer by performing irradiation with a coherent electromagnetic wave to directly excite lattice vibration (phonon).

[Claim 3] A method for forming a semiconductor impurity-doped layer in formation of a semiconductor device using a silicon wafer or a solid including silicon as a substrate, comprising the steps of:

performing activation of an impurity element in a thermally non-equilibrium state to perform low temperature activation of an ultrashallow junction layer by performing irradiation with a coherent electromagnetic wave to directly excite lattice vibration (phonon).

[Claim 4] A method for forming a semiconductor impurity-doped layer described in Claim 2 or 3, characterized in that multipulse irradiation with a coherent electromagnetic wave having an ultrashort pulse is used in irradiation with the coherent

electromagnetic wave, in which a pulse width is 10 to 1000 femtoseconds (a frequency bandwidth is 1 to 100 THz).

[Claim 5] A method for forming a semiconductor impurity-doped layer described in Claim 2 or 3, characterized in that a coherent electromagnetic wave of continuous wave output is used in irradiation with the coherent electromagnetic wave, which has an oscillation frequency or a frequency bandwidth of 10 GHz to 1THz.

[Claim 6] A method for forming a semiconductor impurity-doped layer described in Claim 4 or 5, characterized in that irradiation with a coherent electromagnetic wave is performed concurrently with addition or an introduction process of an impurity element, or is performed after addition or an introduction process of the impurity element.

[Claim 7] A method for forming a semiconductor impurity-doped layer described in any one of Claims 4 to 6, characterized in that a plurality of coherent electromagnetic-wave beams are concurrently incident at a specific angle in irradiation with the coherent electromagnetic wave, so that specific lattice vibration of silicon is excited.

[Claim 8] A method for forming a semiconductor impurity-doped layer described in Claim 4, characterized in that irradiation of a pulse train that has a time interval (10 to 1000 femtoseconds) corresponding to a reciprocal of a specific lattice vibration frequency is performed in irradiation of an ultrashort pulse coherent electromagnetic wave, so that a specific lattice vibration (vibration frequency = 1 to 100 THz) is selectively excited.

[Claim 9] A method for forming a semiconductor impurity-doped layer described in Claim 4 or 5, characterized in that a single or a plurality of coherent electromagnetic-wave beams are incident in irradiation with a coherent electromagnetic wave, so that unspecific lattice vibration is excited.

[Claim 10] A method for forming a semiconductor impurity-doped layer described in Claim 4, characterized in that a silicon surface is melted and solidified by a short time of 10 to 100 femtoseconds in irradiation with an ultrashort pulse coherent electromagnetic wave, so that low temperature activation of an ultrashallow PN junction layer is adiabatically performed.

[Claim 11] A method for forming a semiconductor impurity-doped layer described in any one of Claims 2 to 10, characterized in that a sample is heated concurrently with irradiation of the coherent electromagnetic wave in irradiation with the coherent electromagnetic wave.

[Detailed Description of the Invention]

[0001]

[Technical Field of the Invention] The present invention relates to an annealing method of a solid sample, which has a feature in that, when the solid sample is irradiated with light to directly excite lattice vibration (phonon), vibration, rearrangement, and diffusion of atoms, molecules, and lattice defects are performed in a thermally non-equilibrium state. The present invention particularly relates to formation of a semiconductor impurity-doped layer, which has a feature in that an ultrashallow junction layer is activated at a low temperature in formation of a semiconductor device that includes a silicon single crystal wafer as a substrate.

[0002]

[Prior Art] In recent years, in semiconductor devices such as a very large scale integrated circuit (LSI) that is formed using a silicon single crystal wafer as a substrate, in accordance with reduction of design rules of the semiconductor devices, junction depth of a diffusion layer in a transistor is required to be reduced for speeding-up of the device as well as prevention of short-channel effect. Therefore, in a MOSFET or a bipolar transistor that is used for a dynamic random access memory device (DRAM) or the like, for example, in a device that is achieved with gate length of about 100 nanometers, junction depth of the device is required to be about 50 nanometers, and in a device that is achieved with gate length of about 50 nanometers, junction depth is required to be 10 nanometers. Also, an annealing technique in which an ultrashallow junction layer (about 10 to 50 nanometers) is activated as a semiconductor is examined in addition to a technique in which an ultrashallow junction layer is doped with a semiconductor impurity at high concentration.

[0003] On the other hand, as one of the conventional annealing techniques, an

activation method in a thermal equilibrium state is known, which utilizes solid phase diffusion by infrared rapid thermal treatment (RTA) for entirely heating a solid sample to about 1000 °C with the use of a lamp or the like. As the conventional technique using a laser, a technique in which a silicon surface is irradiated with an XeCl excimer laser of 308 nm to be melted and then recrystallized is known (Reference 1) as laser annealing. Here, for example, thermal treatment in which laser annealing of 0.35 J/cm^2 and RTA at 800 °C for 10 seconds are combined is performed (Reference: Ken-ich Goto, et al., p931-933., International Electron Device Meeting 1999 at Washington DC).

[0004]

[Problems to be solved by the Invention] The conventional annealing technique is effective for activation of an impurity-doped layer, which utilizes a solid phase diffusion process by infrared rapid thermal treatment in a thermal equilibrium state. However, the conventional annealing technique has a problem in that an injected impurity is diffused to a deep part of a substrate when the entire substrate is heated at a high temperature of about 1000 °C even by short-time-heating of about 10 seconds. For example, in a boron atom injecting layer having a thickness of 20 nanometers that is obtained by low energy, there is a problem in that, by rapid thermal treatment at 1000 °C for 10 seconds, the thickness becomes about 50 nanometers, that is, the thickness becomes 2.5 times larger as compared with the thickness before heating.

[0005] In addition, impurity introduction processes are needed to be performed plural times; therefore, in a manufacturing process of an LSI or the like which becomes more complicated, an entire solid sample is heated to a high temperature that is suitable for impurity diffusion in the conventional thermal treatment technique. Therefore, the impurity in the unnecessary part is also diffused.

[0006] Further, in a method using an excimer laser, unnecessary diffusion is significantly suppressed. However, there is a problem in that a leakage current of a formed device gets large.

[0007]

[Means for solving the Problems] In order to solve the above problem, in an annealing

method for a solid sample of the present invention, irradiation of a coherent electromagnetic wave is performed in a plural-pulses manner or a continuous-light manner, which has a frequency bandwidth that is approximately the same as or wider than a frequency of lattice vibration of the solid, and the lattice vibration (phonon) is directly excited coherently, whereby an impurity element is activated in a thermally non-equilibrium state, adiabatically. In addition, in a thermally equilibrium state, a substrate temperature is held to be low so that activation of the impurity element is practically difficult (for example, in a case of a silicon single crystal wafer, less than or equal to 500 °C), whereby a state in which thermal atom diffusion is suppressed is made, and then, activation of an ultrashallow junction layer is performed in that state. Hereinafter, a principle of the present invention will be described in detail.

[0008] In a solid crystal, atoms are regularly arranged, and atomic force acts among the atoms existing in a crystal lattice location. This atomic force acts as restoring force (spring force) according to a Hook's Law with respect to minute displacement; therefore, vibration of atoms generated by thermal motion or forced vibration from outside is transmitted to the next atom, and coupled vibration is caused. This is referred to as lattice vibration, and it is called phonon because it is quantized in a solid body. In addition, atomic force corresponding to mass of the atom, interatomic distance, and a spring constant of restoring force has a particular value for each substance; therefore, a frequency and a wavenumber of the phonon are dependent on each other, which is referred to as a dispersion relation.

[0009] When the solid crystal is irradiated with light, elastic distortion coupled with light is caused by local temperature rise (thermal coupling) or disturbance of dielectric polarization (photoelastic coupling). When the crystal is irradiated with light (electromagnetic wave) in a region of a phonon frequency with this elastic distortion as external force, it is possible to excite coherent phonon with phase alignment by stimulated Raman scattering. For example, according to a dispersion relation of phonon that is known in a silicon single crystal (Reference: for example, F. Favot and A. D. Corso, Phys. Rev. B60, 11427 (1999).), a frequency of phonon is between 10 GHz to 10 THz. In the frequency band (a millimeter wave region) of 10 GHz to 100 GHz, a

millimeter wave oscillating tube such as a gyrotron can be used as a coherent electromagnetic wave in the frequency band. On the other hand, a frequency band of 100 GHz to 10 THz corresponds to an unexplored electromagnetic wave region that is called terahertz radiation, which has not been realized by a single oscillating source.

[0010] Thus, in the frequency band of 10 GHz to 100 GHz, a solid sample is irradiated with a coherent electromagnetic wave in the millimeter wave region that can be obtained by a gyrotron or the like, and the dielectric polarization over a surface of the solid sample is coherently oscillated by an alternating electric field according to a coherent electromagnetic wave, whereby phonon can be excited.

[0011] In addition, in the electromagnetic wave region of 100 GHz to 10 THz which is called terahertz radiation, when two coherent electromagnetic waves having slightly different wavelengths from each other where a frequency is ω1 and ω2 (ω1 > ω2) are incident on a crystal, and a frequency difference ω1-ω2 is set to fulfill ω1-ω2 = ω0 (1) where ω0 is an vibration frequency, stimulated scattering is caused, and then coherent phonon is generated. Therefore, in a case where a coherent electromagnetic wave source is used, which has a spectrum width (a frequency bandwidth) that is wider than ω0, different frequency components in the spectrum each serve as ω1 and ω2 that fulfills the formula (1), and accordingly, this condition is satisfied by the single coherent electromagnetic wave source. The research relating to coherent phonon excitation based on this principle is also used for the physical research including imaging of excited phonon (Reference: Shinichi Nakashima, Muneaki Hase, and Kohji Mizoguchi, "Behavior of Coherent phonons in Femtosecond Region", Journal of the Physical Society of Japan, vol. 53, No. 8, pp. 607-611 (1998); Satoshi Adachi, R.M. Koehl, and K.A. Nelson, "Real-space imaging of phonon-polaritions", Journal of the Physical Society of Japan, vol. 54, No. 5, pp. 357-363 (1999)).

[0012] Since a pulse width (Δt) and a frequency bendwidth (Δω) in a coherent electromagnetic-wave beam satisfies Δt · Δω < 2ln2/π (2), a frequency bandwidth becomes 1 to 100 THz in a coherent electromagnetic wave of which a pulse width is 10 to 1000 femtoseconds, which can be generated with the use of a titanium-sapphire laser device or the like, and it is possible to satisfy the formula (1) with the use of a

difference frequency in a frequency region.

[0013] Therefore, the present invention has a feature that a solid sample is irradiated with light to directly excite lattice vibration (phonon) as described in Claim 1. Accordingly, vibration, rearrangement, and diffusion of atoms, molecules, and lattice defects are selectively performed in a portion irradiated with light in a state where thermally atomic diffusion is suppressed, and then annealing of the solid sample can be realized. That is, in a practical manufacturing process of a semiconductor device, since annealing of the solid sample is performed without rising temperature of the entire solid sample to a high temperature, annealing for only a portion that is selectively opened can be performed by irradiation with light in a state where an appropriate resist material is formed. Therefore, an impurity diffusion profile in a manufacturing process of a semiconductor device such as an LSI that becomes more complicated hereafter can be precisely controlled, which can contribute to manufacture of a high-performance semiconductor device.

[0014] The present invention has another feature that, in the formation of a semiconductor over a silicone wafer, lattice vibration (phonon) is directly excited by irradiation with a coherent electromagnetic wave, whereby activation of an impurity element is performed in a thermally non-equilibrium state, low-temperature activation of an ultrashallow junction layer is performed, and then a semiconductor impurity-doped layer is formed as described in Claim 2.

[0015] The present invention has another feature that, in the formation of a semiconductor device using a silicon single crystal wafer as a substrate, lattice vibration (phonon) is directly excited by irradiation of a coherent electromagnetic wave, whereby activation of an impurity element is performed in a thermally non-equilibrium state, and activation of an ultrashallow junction layer at a low temperature is performed as described in Claim 3.

[0016] The present invention has another feature that multi-pulse irradiation with a coherent electromagnetic wave having an ultrashort pulse in which a pulse width is 10 to 1000 femtoseconds (a frequency bandwidth is 1 to 100 THz) is used as described in Claim 4.

[0017] The present invention has another feature that a coherent electromagnetic wave of continuous wave output that has an oscillating frequency or a frequency bandwidth of 10 GHz to 1 THz is used as described in Claim 5.

[0018] The present invention has another feature that irradiation with the coherent electromagnetic wave described in Claim 4 or 5 is used concurrently with or after addition or introduction process of an impurity element as described in Claim 6.

[0019] The present invention has another feature that, in irradiation of the coherent electromagnetic wave described in Claims 4, 5, and 6, a plurality of coherent electromagnetic-wave beams are concurrently incident at a specific angle, whereby specific lattice vibration of silicon is excited, and then a semiconductor impurity-doped layer is formed as described in Claim 7. For example, in a case where two coherent electromagnetic waves are used, a distance (Λ) of an interference fringe of light and shade that are generated over crystal can be represented by the following formula with the use of a tolerance angle (θ) of two beams and a center wavelength (λ) of a coherent electromagnetic-wave beam.

[0020] $\Lambda = \lambda / [2\sin(\theta/2)]$ (3)

This interference fringe gives periodic disturbance to crystal spatially to generate photoelastic distortion. As a result, it is possible to excite phonon that has a wave number that is approximately equal to a wave number (k) of diffraction gratings that are excited.

$$k = 2\pi / \Lambda \quad (4)$$

[0021] The present invention has another feature that, in irradiation with the ultrashort pulse coherent electromagnetic wave described in Claim 4, irradiation of a pulse train having a time interval (10 to 1000 femtoseconds) corresponding to a reciprocal of a specific lattice vibration frequency is performed, whereby a specific lattice vibration (vibration frequency = 1 to 100 THz) can be selectively excited as described in Claim 8.

[0022] The present invention has another feature that, in irradiation with a coherent electromagnetic wave described in Claims 4 and 5, single or a plurality of coherent electromagnetic wave beams are incident, whereby lattice vibration of a plurality of modes can be excited as described in Claim 9.

[0023] The present invention has another feature that, in irradiation of the ultrashort pulse coherent electromagnetic wave, a silicon surface is melted and solidified in a short time of 10 to 100 femtoseconds, whereby activation of a ultrashallow PN junction layer at a low temperature is performed adiabatically as described in Claim 10.

[0024] The present invention has another feature that, in irradiation of the coherent electromagnetic wave, a substrate is heated to a low temperature (for example, in a case of a silicon single crystal wafer, less than or equal to 500 °C) at the level where activation of an impurity element is practically difficult in a thermal equilibrium state concurrently with irradiation with the coherent electromagnetic wave as described in Claim 11.

[0025]

[Embodiment Mode of the Invention] Hereinafter, an annealing method of a solid sample, a technique for forming a semiconductor impurity-doped layer, and a device thereof, each of which relates to the present invention will be explained with reference to drawings.

[0026]

(Embodiment Mode 1) An embodiment of the present invention relating to Claims 1 to 6, 9, and 10 will be explained with reference to FIGS. 1 and 2. This embodiment relates to an impurity in a silicon substrate. As shown in FIG. 1, an impurity is introduced by, for example, ion injection or plasma doping, and a silicon substrate 1 over which an impurity layer 2 is formed in advance is irradiated with a coherent electromagnetic wave 3 from a side of a surface where the impurity layer 2 is formed to directly excite phonon in a solid, whereby activation of the impurity element is performed in a state in which the silicon substrate 1 is held at a low temperature (for example, in a case of a silicon single crystal wafer, less than or equal to 500 °C) where activation of the impurity element is practically difficult in a thermally equilibrium state. It is to be noted that the object to be processed is a silicon substrate in this embodiment; however, it is also possible to use a substrate using a glass material, a high molecular material, or the like over which a silicon film or the like is formed or a compound semiconductor substrate such as GaAs or the like. In addition, there is no problem if a

mask material such as a photoresist or the like is used according to need.

[0027] For irradiation with the coherent electromagnetic wave, a method described below was typically used. In FIG. 2, a solid sample 14 such as a silicon substrate is placed on a sample stage 15 set in a chamber 13. Then, an incident coherent electromagnetic wave 16 generated by a coherent electromagnetic wave source 11 is converted into an appropriate irradiation coherent electromagnetic wave 17 through an irradiation optical system 12 that is formed using a predetermined optical component that is needed for securing irradiation uniformity or the like, and the solid sample 14 is irradiated therewith. The chamber 13 was held under an inert gas (for example, nitrogen, helium, or argon) atmosphere or a vacuum of less than or equal to 1×10^{-6} Torr (1Torr = 133.322 Pa). It is to be noted that, in the embodiment shown in FIG. 1 or 2, the objected to be processed was a silicon substrate over which an impurity layer is formed in advance. However, there is no problem if an impurity layer is formed by an ion source added to the chamber with the use of a substrate before formation of the impurity layer or if irradiation with a coherent electromagnetic wave is performed concurrently with formation of an impurity layer by plasma doping in electric discharge that is generated by flow of diborane or the like as a gas including an impurity in the chamber.

[0028] As for the incident coherent electromagnetic wave 16, ultrashort pulse laser light, continuous wave output laser light, and a millimeter wave band electromagnetic wave are singly used or are combined to be used. The ultrashort pulse laser light has a pulse width of 10 to 1000 femtoseconds (the frequency bandwidth is 1 to 100 THz). The continuous wave output laser light has a frequency bandwidth of 10 GHz to 1 THz. The millimeter wave band electromagnetic wave has an oscillating frequency of 10 GHz to 100 GHz. The ultrashort pulse laser light can be generated, for example, by utilization of a titanium-sapphire laser device for the coherent electromagnetic wave source 11. The continuous wave output laser light can be generated, for example, by utilization of a semiconductor laser device for the coherent electromagnetic wave source 11. The millimeter waveband electromagnetic wave can be generated by utilization of a gyrotron oscillating tube, a klystron oscillating tube, or a progressive wave tube for

the coherent electromagnetic wave source 11.

[0029] In activation of the impurity layer of the object to be processed for which the ultrashort pulse laser light is used, there is no problem, even in a case where the vicinity of an uppermost surface of the object to be processed is melted by irradiation with the pulse laser light, because a melting and solidifying phenomenon including the impurity layer is adiabatically and locally caused. This is because influence given to a temperature of the entire object to be processed is negligibly small by the ultrashort pulse in which a pulse width is 10 to 1000 femtoseconds.

[0030] FIG. 3 shows a boron concentration profile of a case in which irradiation with ultrashort pulse laser light that is generated from the titanium-sapphire device is used and a case in which conventional infrared rapid heating is used in order to activate a p-type impurity layer with a depth of 20 nm, which is formed by introduction of boron impurity with dose of 1×10^{15} ions /cm^2 to a single crystal silicon wafer substrate. In an embodiment shown in FIG. 3, ultrashort pulse laser light with a center wavelength of 820 nm and a pulse width of 150 femtoseconds, which is generated with the use of a titanium-sapphire laser device in a nitrogen gas atmosphere, was vertically incident on the object to be processed in a state where a temperature of 20 °C is held. In the conventional infrared rapid heating that is shown in FIG. 3 for comparison, a surface temperature of the object to be processed was held at 1000 °C for 10 seconds. As a boron concentration profile after activation treatment by the conventional infrared rapid heating, boron was thermally diffused to a deep part of a substrate, and the depth of the formed junction was 42 nm, which was a greater than or equal to double a thickness of the impurity introduction layer. On the other hand, in this embodiment in which irradiation with ultrashort pulse laser light is used, boron is not significantly diffused to a deep part of the substrate as compared with the state before activation treatment, and it can be found that an ultrashallow junction of which junction depth is 20 nm is formed. In accordance with the structure as described above, the object to be processed is irradiated with a coherent electromagnetic wave from a side of an impurity formation surface, and phonon in a solid is directly excited, whereby activation of an impurity element can be performed in a state where the object to be processed is held at a low

temperature (for example, in a case of a silicon single crystal wafer, less than or equal to 500 °C) at the level where activation of the impurity element is practically difficult in a thermally equilibrium state.

[0031] Further, as for a low temperature activation of an impurity layer, one or a combination of ultrashort pulse laser light, continuous wave output laser light, and a millimeter wave band electromagnetic wave can be singly used or combined to be used, as the coherent electromagnetic wave in addition to the embodiment of FIG. 3. The ultrashort pulse laser light has a pulse width of 10 to 1000 femtoseconds (a frequency bandwidth is 1 to 100 THz), the continuous wave output laser light has a frequency bandwidth of 10 GHz to 1 THz, the millimeter wave band electromagnetic wave has an oscillating frequency of 10 GHz to 100 GHz.

[0032]

(Embodiment Mode 2) An embodiment of the present invention relating to the invention of Claim 7 will be explained with reference to FIG. 4. FIG. 4 shows an embodiment where an irradiation method is used, in which a plurality of coherent electromagnetic-wave beams are incident at a specific angle concurrently. As shown in FIG. 4, an impurity is introduced, for example, by ion injection or plasma doping, and a silicon substrate 21 over which an impurity layer 22 is formed in advance is irradiated with a plurality of coherent electromagnetic-wave beams from a surface side where the impurity layer 22 is formed. For example, in a case of using two coherent electromagnetic-wave beams L1 and L2, an interference fringe having a distance (Λ) in accordance with the formula (3) is generated over a surface of the sample to be processed by utilization of a tolerance angle (θ) of two beams and a center wavelength (λ) of the coherent electromagnetic wave beams. This interference fringe can give periodic disturbance spatially to a sample surface to generate photoelastic distortion so that lattice vibration can be selectively excited, which has the wave number approximately equal to the wave number (k) of the excited diffraction grating obtained by the formula (4). The phonon having a specific wave number is directly and selectively excited over a surface of the solid sample, whereby the impurity element can be activated in a state where the silicon substrate 21 is held at a low temperature (for

example, in a case of a silicon single crystal wafer, less than or equal to 500 °C) at the level where activation of the impurity element is practically difficult in a thermal equilibrium state.

[0033] Here, in the relation between the wave number and attenuation factor in the solid of the excited phonon, it is made known that the attenuation factor becomes larger in the phonon of the high wave number region according to physical research on imaging of phonon (Reference: Satoshi Adachi, R.M. Koehl, and K.A. Nelson, "Real-space imaging of phonon-polaritions", Journal of the Physical Society of Japan, vol. 54, No. 5 (1999), pp. 357-363). Therefore, as the wave number of the excited phonon becomes larger, excited energy can be imparted to the shallower region that is in the vicinity of the surface of the object to be processed. In other words, a tolerance angle (θ) of two beams and a center wavelength (λ) of a coherent electromagnetic-wave beam are appropriately selected, and phonon with a specific wave number is selectively excited, whereby there is an effect that a thickness of the processing region from the surface of the object to be processed to a deep part of the substrate can be controlled.

[0034] It is to be noted that the object to be processed is a silicon substrate in this embodiment; however, it is possible to use a substrate using a glass material, a high molecular material, or the like, over which a silicon film or the like is formed; or a compound semiconductor substrate using GaAs or the like. In addition, there is no problem if a mask material such as a photoresist is used according to need.

[0035] Further, as for the incident coherent electromagnetic-wave beam, ultrashort pulse laser light, continuous wave output laser light, and a millimeter wave band electromagnetic wave are singly used or are combined to be used. The ultrashort pulse laser light has a pulse width of 10 to 1000 femtoseconds (the frequency bandwidth is 1 to 100 THz). The continuous wave output laser light has a frequency bandwidth of 10 GHz to 1 THz. The millimeter wave band electromagnetic wave has an oscillating frequency of 10 GHz to 100 GHz. The ultrashort pulse laser light can be generated, for example, by utilization of a titanium-sapphire laser device. The continuous wave output laser light can be generated, for example, by utilization of a semiconductor laser device. The millimeter waveband electromagnetic wave can be generated by

utilization of a gyrotron oscillating tube, a klystron oscillating tube, or a progressive wave tube.

[0036]

(Embodiment Mode 3) An embodiment of the present invention relating to the invention of Claim 8 will be explained with reference to FIG. 5. FIG. 5 relates to irradiation with the ultrashort pulse coherent electromagnetic wave shown in Embodiment Mode 1 or Embodiment Mode 2, and shows a timing chart of a pulse in an embodiment in which irradiation of a pulse train that has time intervals T3 (10 to 1000 femtoseconds) corresponding to a reciprocal of a specific lattice vibration frequency is performed. With the use of a plural pieces of NP (5 in an example of FIG. 5) of ultrashort pulse laser light (a pulse width PD = 10 to 1000 femtoseconds), a surface of an objected to be processed is irradiated with the pulse train having time intervals T3 (10 to 1000 femtoseconds) corresponding to a reciprocal of a specific lattice vibration frequency (pulse irradiation time: T2 = T3xNP) in every pulse train irradiation period T1 (repetition rate of the pulse train: 1/T1). In accordance with such a timing chart structure of pulse irradiation, a reciprocal of the pulse interval T3 (1/T3) is equalized with a specific lattice vibration (vibration frequency = 1 to 100 THz), whereby the phonon having a vibration frequency of 1/T3 can be selectively excited. In addition, for selective excitation of a specific lattice vibration in the solid using the pulse train, it is proved that excitation selectivity of the specific phonon is improved with increase in the pulse number used for the pulse train in mixed crystal of $Bi_{0.31}Sb_{0.69}$ (Reference: Shinichi Nakashima, Muneaki Hase, and Kohji Mizoguchi, "Behavior of Coherent phonons in Femtosecond Region", Journal of the Physical Society of Japan, vol. 53, No. 8 (1998), pp. 607-611). Further, for example, in a case of forming a p-type semiconductor layer over a silicon substrate, only an oscillation mode between Si-B is selected, whereby only a boron impurity layer is selectively excited, and there is an effect that unnecessary diffusion to a silicon region existing at a deep part of a substrate is suppressed.

[0037] According to a technique for forming a semiconductor impurity-doped layer relating to the invention of Claim 11, a substrate is heated to a low temperature (for

example, in a case of a silicon single crystal wafer, less than or equal to 500 °C) at the level where activation of an impurity element is practically difficult in a thermal equilibrium state concurrently with irradiation with coherent electromagnetic wave, whereby recovery of a defect formed in an impurity layer by ion injection, plasma doping, or the like is promoted. Therefore, a predetermined impurity layer can be activated in a short time as compared with a case in which the substrate is not heated.

[0038]

[Effect of the Invention] According to the present invention, an ultrashallow semiconductor impurity-doped layer can be formed with high accuracy.

[Brief description of the Drawings]

[FIG. 1] A cross-sectional view showing an irradiation method of a coherent electromagnetic wave relating to Embodiment Mode 1 of the present invention.

[FIG. 2] A cross-sectional view of a coherent electromagnetic-wave irradiation device relating to Embodiment Mode 1.

[FIG. 3] A graph showing a boron concentration profile in a case of using ultrashort pulse laser light irradiation and in a case of using infrared rapid heating.

[FIG. 4] A cross-sectional view showing an irradiation method of a coherent electromagnetic wave relating to Embodiment Mode 2 of the present invention.

[FIGS. 5a and 5b] A timing chart of a pulse in an embodiment where irradiation of a pulse train relating to Embodiment Mode 3 of the present invention is performed.

[Reference Numerals]

1. silicon substrate

2. impurity layer

3. coherent electromagnetic wave

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